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System for Robot Control Inspired By the Functionality and Organisation of the Human Nervous System

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ABSTRACT

This paper presents a model of a control system for robot systems inspired by the functionality and organisation of human neuroregulatory system. Our model was specified using software agents within a formal framework and implemented through Web Services. This approach allows the implementation of the control logic of a robot system with relative ease, in an incremental way, using the addition of new control centres to the system as its behaviour is observed or needs to be detailed with greater precision, without the need to modify existing functionality. The tests performed verify that the proposed model has the general characteristics of biological systems together with the desirable features of software, such as robustness, flexibility, reuse and decoupling.

Keywords: *Robots control, Nervous system, Bio-inspired control, Layered control*

1. INTRODUCTION

Robotics has currently become one of the most active fields for researchers and has wide repercussions for all society, changing our way of thinking about our daily lives. Examples of where the application of robots has captured the world's attention are nuclear accidents, finding shipwrecks, exploring volcanoes and space travel. They have changed the way in which we build, how we remain safe, and how we produce and distribute energy and food throughout the world [1]. Their high degree of involvement in society has made the diversity and variety of robots as great as the tasks to which they are put [2].

The design of a robot is inherently multidisciplinary and the design and implementation of its control software is one of the most important aspects [3]. There are a huge number of questions to be taken into account and in the majority of cases these are finally resolved by *ad hoc* solutions. Thus there are groups of researchers specialising in the creation of generic control architectures for robots [4], trying to minimise the effort required in the design of the control system, so that more effort can be focussed on the implementation of the functionalities necessary for a robot to undertake the tasks for which it was conceived.

Precisely because the final intention is to construct a control system for an intelligent autonomous robot, many authors opt for using the human neuroregulatory system as a model, or at least as a starting point, for the characterisation of the control system [5] as this is the most complete control system known, or at least partially known.

This article presents a proposal for a generic control system for a robot system based on software agents and inspired by the functionality and organisation of the human neuroregulatory system. The article is structured as follows: section 2 presents a review of the more important work in this field; section 3 introduces the model of the proposed control system; section 4 describes a case study; section 5 presents the implementation and validation of the system; and finally, section 6 extracts the main conclusions of the work and proposes future lines of research.

2. BACKGROUND

The robot control system can be qualified as deliberative, reactive, hybrid or behaviour-based [6]. These system may either have a centralised architecture (in the majority of deliberative and hybrid systems) or decentralised architecture (reactive or behaviour-based systems) [6]. In general, a system is often either orientated towards more reactive or more deliberative characteristics [7]. However, when it is desired for a robot to have autonomy in its functionality, both capacities are necessary. Reactive capabilities are often associated with lower level behaviours that ensure proper functioning of the robot and the execution of simple tasks (motor movement, measuring distances, etc.), while deliberative capabilities are associated with higher level behaviours allowing a robot to plan, follow strategies and correct errors in the execution of tasks [8]. Because the functional conception of systems is common, various authors have made proposals with the aim of generalising the control system to allow for any functional modules that need to be implemented, and generally using decentralised architectures allowing for the addition of independent modules without the need to recompile the complete system [8].

One of the first authors to express the need for a control architecture was Brooks [9], who presented what he called the Subsumption Architecture. This proposal was one of the first to break with the traditional AI architectures in favour of moving closer towards a bio-inspired natural structure. Its main contribution consisted in a functional decomposition based on behaviours or levels of competence, functionally similar to that of biological system. This decomposition had limitations, such as for example being too reactive and with an unstructured implementation.

Later, various architectures were developed based on different approximations. Although many of them were conditioned by the particular application for which they were employed, they reflected a certain parallelism with biological systems.

A multi-level development based on the design and analysis of action-orientated perception systems is presented in [10]. This proposal tried to emulate the approach and avoidance behaviours of frogs in a robot. It was based on the analysis of animal behaviour followed by its subsequent implementation in a robot using a model of a control structure in the form of automata-type interactions of system networks called schemas.

The 4D/RCS architecture [11] proposed a multi-level and multiple hierarchical resolution system formed by computational nodes, like neuronal centres, in which each includes sensory processing, world modelling, value judgement and behaviour generation. This architecture provides functional definitions of elements, sub-systems, interfaces, entities and relations, supports the selection of objectives, signal processing, integration and consolidation of new knowledge and value representation. Each of the processing nodes somewhat resembles the neuroregulatory centres of biological systems. This proposal exhibits high complexity in the implementation of higher levels because, as indicated in the paper, the lower levels have been *more or less implemented* and it is precisely the integration of the deliberative levels that presents the greatest problems.

In CLARAty [12], the Jet Propulsion Laboratory and NASA proposed a solution developed on two levels in which they attempted to achieve simple integration between the reactive and deliberative levels. Although the proposal was innovative, its implementation was too dependent on the robot that it tried to control. The granularity established between both levels depended on the functions to be performed and, therefore, the communication mechanisms between both layers were also variable. However, the use of two single levels is interesting in that it breaks with the traditional perception-planning-execution scheme.

The LAAS architecture in [13] is again structured in 3 levels: decisional, executive and functional. The main objective in this paper was to homogenise the development of mobile robots and enable module reuse. The main requirements were programmability or flexibility, autonomy and adaptation, reactive capacity, consistent behaviour, robustness and extensibility. A robot needs to be capable of being used for various tasks, to have the capacity to add or remove modules, so it is sufficiently reactive to respond to sudden stimuli and alerts, and always in harmony with a behaviour that seeks to achieve the global objective. A large contribution by this proposal are the specific tools for the development of control systems and the ultimate aim is the need to make the implementation independent of the hardware.

Arkin proposed the AuRA architecture [14] based on a hybrid control architecture of two blocks, the deliberative and the reactive. Each of the blocks uses a different method to resolve problems. The deliberative part uses the techniques of artificial intelligence, while the reactive part uses control schemas and these are in charge of directing behaviour processing. In the normal state, schemas generated at the reactive level are used, with the deliberative level remaining on standby. When an impossible situation arises, the deliberative block comes into action.

An interesting paper is the proposal described in [15]. Here, the fundamentals about a robot's autonomy are reviewed and it is concluded that a system must be as sufficiently autonomous as the context demands, making it possible for a robot to take or not take decisions and defining the level to which it should take decisions. It was with this idea that HARPIC was proposed, which, in addition to establishing limits to decision taking, enables the integration of learning algorithms. This architecture is also noteworthy for its similarity to biological systems and the need for parallelism between both structures if a behaviour that is similar as regards autonomy and intelligence is desired.

In many of these architectures, the parallelisms with respect to biological systems described in [16] are found. These are the functional division of the system and its organisation into multilayer systems, hierarchical control systems divided into competencies, control loops at each level and modules specialising in tasks within generic control modules. In general terms, the neurological system has evolved incrementally over the last few thousand years through the addition of layers and levels that improved, perfected or supplemented the activities at a lower level. Specialised zones also arose within these levels for the performance of tasks such as mathematical calculation, pattern association and learning and control of reflective actions. These features were proposed in [17], where the dissociation between the deliberative and reactive levels of the nervous system were described. Later research such as [18] and [19] developed further this type of dissociation and structuring of the nervous system.

Using the nervous system as a source of inspiration is not only focussed on its functional organisation but also on its morphology. Many studies [20][21][22][23] established that the basic morphology of the brain is similar from the earliest phases of vertebrate evolution. Furthermore, the major morphological divisions of the brain (spinal cord, hindbrain, midbrain, diencephalon, telencephalon) is present in all classes of vertebrates, even in some fossils. This indicates that the structure of the vertebrate nervous system in its basic morphology has existed for a least the last four hundred million years, or even earlier [22], and has been evolving to the present day. This evolution has taken place conservatively, through the incremental addition of new regions or layers, which have complemented or modulated the earlier systems [24]. It can also be seen that the development of the brain has proceeded from the centre towards the external layers, with a migration of neurones towards the sides and peripheral positions that differentiates and specialises them [25]. The more general systems, therefore, the functions most directly related to the physical system, are located centrally and the more specialised systems, those containing more complex and indirect functionality, are located on the periphery of the nervous system.

Although parts of the nervous system continue to be unknown, its study and characterisation has enabled the extraction of models of the neuroregulatory system, such as that presented in [26], reflecting the organisation and functionality of the system. This model is based on the analysis of the neuroregulatory system, which is formed by various regulatory centres. Each of these centres is in charge of regulating a series of afferent signals and generating efferent signals directed towards the mechanical system or other regulatory centres. Once the centres have been established, a model of the regulator based on agents is constructed. Systems based on agents provide a paradigm that is capable of providing sufficient expressive capacity to model non-linear systems and systems with unknown parameters. Each centre is modelled as a PDE-type agent (perception-deliberation-execution) that contributes partial control over the system. The emergent behaviour from the sum of all the contributions of each agent provides a behaviour that is similar to that of the lower urinary tract neuroregulator.

These models have also been extended to other very different types of systems such as computer networks [27]. This demonstrates that the human nervous system, biologically evolving and improving over the last four hundred million years, is an example and efficient model of a control system in a large number of scenarios and contexts. Its implementation through the agent paradigm provides expressive power for systems where part of the behaviour is not known and where it is also necessary to increment the system as partial behaviours of the parts become known.

Our proposal is based on these types of models as it has been demonstrated that they can function appropriately to model both biological systems and non-linear systems in general and can be at least partially known.

3. PROPOSED CONTROL SYSTEM

Various robot architectures have been described over the last few years that have strengths and also weaknesses. Our proposal is based on taking advantage of the strengths but from a biological point of view as a base for the construction of a control system for autonomous mobile robots. We describe a control system from a biological point of view, establishing the fundamentals of the system and we also specify which features should be maintained from the point of view of software architecture.

3.1. Biological characterisation

A control system based on the human neuroregulatory system must follow a set of architectonic principles described below.

It must be a multi-layered system. In a multi-layered system, the functions are divided so that the lower levels perform the more reactive or automatic activities while the higher levels are responsible for the deliberative or cognitive activities. The number of layers only depends on the complexity of the system, increasing as more cognitive functions are performed.

Layers divided in control centres. Within each layer, there are control centres specialised in performing particular tasks (servo control, treatment and adaptation of data inputs, etc.). Each control centre performs a particular task and together they provide a complete emergent behaviour of the system. Each regulating centre is responsible for perceiving or receiving data, which it uses to select the action to perform and launches it to the system. This action can be executed on another centre or on physical elements. Each control centre must also possess memory, at least at middle and higher levels, to maintain its internal state and the state of the known world that it can perceive.

Semi-autonomy of functions. Each of the control centres is autonomous in its functioning; it receives, processes and sends data from or towards other centres of physical elements. An element is independent in so far as to perform its tasks, it only needs to receive data. But, in the same way as a biological system, if one centre goes down, the others continue to be active and only suppress certain specific tasks or the accuracy with which they can perform such functions.

Horizontal and vertical interconnection between centres. Regulatory centres can be interconnected with other centres of the same layer or with centres at higher or lower layers and not necessarily contiguous layers.

Control loops. Higher layers must control or modulate the activity of lower levels to the point of being able to suppress their activity. Each layer also exercises a control loop as it will receive as input the results of its contribution to the control of the system.

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Division of functionalities. In the same way as in a real neuroregulatory system, when an area or centre contains various functions, there is a division of this centre into several that exercise each task separately, thereby specialising their execution.

Reactive autonomy. The functions located on the reactive levels must be sufficiently autonomous to be able to ensure their correct functioning. For example, the functions related with the robot's movements. They must also allow a certain degree of learning so that functions that are always repeated in the same way and initially require a deliberative level for their achievement are displaced to reactive levels.

3.2. Software features

From this point of view, the main principles are described below.

Modularity. A system must be modular to ensure its maintainability, code reuse, flexibility and good structured.

Decentralisation. A system must be decentralised to allow scalability and provide robustness, in addition to facilitating multi-objective systems. Of course, decentralisation will allow the optimisation of resources locating each module in the computation system where it is most appropriate, or even allowing its dynamic displacement at execution time.

Based on standards. The use of standards for system implementation ensures three basic aspects: that it can be ported to all those platforms that comply with the standards, that there will be a community to support it, and lastly, that it is based on good practices and the experience of a broad set of experts.

Safety and security. The system must provide safety and security in achieving the objectives, that is, while it is watching over the achievement of the objectives it is also watching over the integrity of the robot system. To achieve this, it must ensure that all components involved are kept active and ready to start operating, that they meet response times so that if a module fails, another module can be sought that could exercise the lost function or try to continue with execution.

Homogeneity. Although there are clearly reactive and deliberative functions in an autonomous system, the implementation should provide homogeneity of the system. On one hand, irrespective of the layer in which the central regulator is located, its internal structure is always homogenous. On the other hand, all physical devices, functionalities, tasks, planners, etc. are viewed as elements at the same level of abstraction, with the same communicational capacities and integrated in a common architecture.

3.3. Model

As we have analysed in Section 2, there are models extracted from biological systems that, using the agents paradigm, allow the expression of system behaviour and its control functions. Based on these models and the features of the control system described above, we can establish the following equivalences.

Table 1: Equivalences between the neuroregulatory system and the robot control system.

Biological Control System	Robot Control System
Neuroregulatory Centre	Control Centre - *cc*
Biological-Mechanical system	Robot-Mechanical system
Neuronal connections	Connections between *cc*
Nerve impulses	Signals and variables

Through these equivalences, we can model the control system of a robot as a set of control centres specialising in performing local tasks and which, together, as emergent behaviour, achieve the global objective of the system. It is the influences exercised by each of the control centres that results in the robot's behaviour.

Graphically, the system is shown in Figure 1. The system is composed of control centres (*cc*). The *cc* closest to the physical system are those responsible for modulating communication between them and their actions will be more reactive in type. At higher levels of control, hybrid tasks are performed (for example, calculating the actual position of the robot according to the movement described by the motors) or purely deliberative tasks (for example, tracing a correction produced by an error in the robot's movement). Each *cc* will receive input messages from other *cc* or will send messages to other *cc*. The suppression of the activity of a *cc* only results in the loss of its own functionality. For example, if the *cc* in charge of monitoring drops in front of the robot goes down, the robot could fall down stairs, but will continue to have its functionalities of movement.

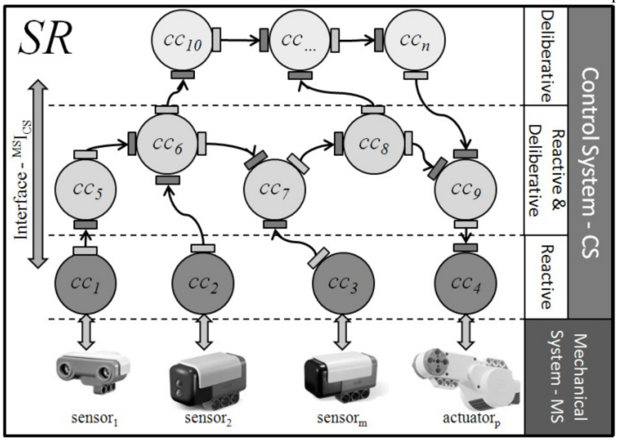

Figure 1: Proposed model.

Using the formal framework proposed in [26], our model of the control system is formally expressed through the tuple, $SR = <MS, CS, {}^{MS}I_{CS}>$.

Where *CS* models the control system, *MS* models the mechanical system and ${}^{MS}I_{CS}$ describes the relations between both parts; basically the complex system of interconnection between the control centres, equivalent to the neuronal connections of the neuroregulatory system.

In our case, it is not necessary to model the mechanical system *MS* as this will be responsible for perceiving the state of the world through various sensor devices and transmitting the actions through its actuators, behaving as the environment dictates and the laws of reality.

Each of the *cc* making up the whole of *CS* is formally defined as the tuple $\langle \Phi_i, S_i, Percept_i, Mem_i, Decision_i, Exec_i \rangle$.

Where Φ_i corresponds to the set of perceptions of the control centre, that is, to those signals that the centre can perceive and which are of interest to it. S_i is the set of internal states of the control centre. $Percept_i$ is the function of perception, that which provides information to the neuronal centre on the state of the system. Mem_i is the function of memorising, that which gives the control centre the capacity to be conscious of its own state stored in the S_i. $Decision_i$ selects which is the next task to be executed. And $Exec_i$ represents the intention held by the control centre to act on the system; it is the execution function that produces efferent signals towards other control centres.

The set of possible states associated with a specific control centre is defined as $\langle \sigma_1, \dots \sigma_n \rangle$. Where each σ_j is a structure composed of a list of pairs formed by an element and its value corresponding to the state of the system.

The function of *perception* represents the quality of being capable of classifying and distinguishing the system states it regulates. Perception is defined as a function that associates a set of values, called perceptions or stimuli, with a set of system states defined by $Percept_i: \Sigma \rightarrow \Phi_i$.

The internal states of the control centre represent what it can remember, allowing it more complex behaviours, defined as $\langle s_1, \dots s_n \rangle$.

The function of *decision* defines a task dependent on the perception that the control centre has and on its internal state, formally, $Decision_i: \Phi_i \times S_i \rightarrow P$.

The function of *memorising* associates an internal state of the control centre with its current perception to give it memory $Mem_i: \Phi_i \times S_i \rightarrow S_i$.

Once the action to perform has been determined, the function of *execution* carries it out $Exec_i: P \times \Phi_i \rightarrow \Gamma$. Where Γ represents the set of influences of the various control centres.

3.4. Specification of control centres

To be able to specify which are the control centres, it is necessary to have a method to decompose a behaviour into the centres responsible for each of the tasks to be performed. To do this, we can use the heuristic proposed in [6]. From the general description of a behaviour, this heuristic allows us to determine the actions into which it can be divided, and for the actions, into which manipulation of signals they can be translated. This heuristic frames the actions to be performed, and the granularity to achieve in the division of actions will have as a limit those actions that manipulate simple variables (the signal-value pairs that compose the internal states of a control centre). The heuristic comprises the following steps:

1) Specifying the desired behaviour in qualitative terms. Describing the global objective of the system.

2) Specifying the behaviour in terms of actions. It is the process of decomposing the behaviour into independent actions serving as sub-objectives of the global objective.

3) Specifying the actions in terms of the robot's effectors. Selecting from the set of actions and deciding on the granularity of these depending on the degree of fineness with which the tasks must be performed.

Step 2 is repeated as many times as necessary in order to reach step 3.

4. CASE STUDY

As a case study and by way of example, we describe using a robot composed of various servo-motors and sensors located in a unstructured and dynamic environment. The robot must move autonomously from point A to point B. The environment, the robot, the behaviour to implement, the proposed model and the development platform are described below.

4.1. Environment

The robot moves in an unstructured environment. That is, there are no marker or localisation elements specially designed for the robot's movement.

This environment is also dynamic; it will be subjected to interferences and changes, such as for example the appearance of new elements, people crossing, disappearance of objects, noises, changes in illumination, etc.

In our case, this environment is located in one of the actual laboratories of the University of Alicante, in which people are working.

The robot locates itself through the measurement by its servos of space covered, and by its acceleration and direction sensors that indicate if it is moving and if the direction taken is correct.

4.2. Robot

We used a Lego robot as a base for our proposal. The flexibility of this platform allowed us to construct any robot, with more or fewer sensors or mechanical systems. The purpose of our work was not the construction of an efficient and multitasking robot with high capabilities, but a control system able to function correctly in any physical support. In our case, the robot (Figure 1) was composed of:

- 2 NXT bricks connected to the PC via Bluetooth.
- An array of 3 sonic sensors to detect obstacles to the front.
- An array of 2 sonic sensors to detect the floor.
- A magnetic compass used for tracing trajectories in a particular direction and for knowing the robot's orientation.
- 2 NXT motors to perform the robot's movements.

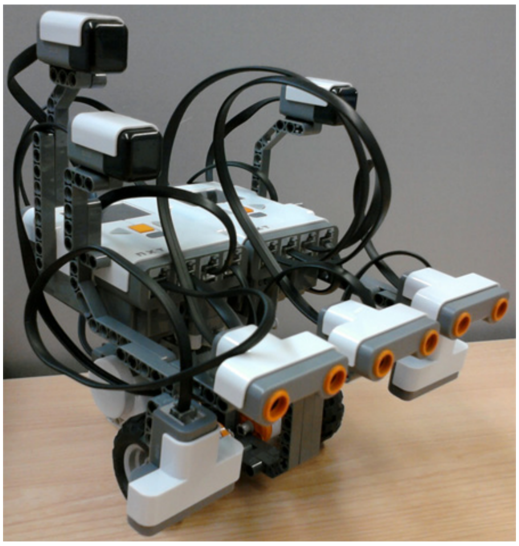

Figure 2: Robot used in the tests

4.3. Behaviour

The behaviour we wished to implement was the movement of the robot through the environment, from the point where it started to another point located at a distance and a certain direction (for example, "move 10 metres direction north"). Two approximations were defined for this behaviour. A first, in which only the movement was defined, and a second in which, in addition to moving, it also had to avoid obstacles. In order to define the systems, we used the heuristic proposed in Section 3.2 as a base, defining 3 levels of detail to arrive at the specific actions:

- Level 1: general description of the behaviour.
- Level 2: behaviour in terms of actions.
- Level 3: actions in terms of effectors.

4.3.1 Behaviour 1: robot that moves from A to B

Level 1: given a specific point where the robot currently is located, initially (0,0), it must move to a destination point (A,B).

Level 2: (1) be capable of communicating with the hardware (to receive sensor values or to communicate values to motors), (2) know the current position as a function of the movements performed, (3) calculate the distance and the direction necessary to reach the objective, (4) perform the movement of the robot.

Level 3: the following table describes in each module; what communication takes place, module of origin, module of destination and signals transmitted.

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Table 2: Description of the signals transmitted between modules

cc	S	T	Signal
1	4	1	(V1,V2) motor speeds
	1	2	(a1, a2, …, an). Servo and sensor values
2	1	2	(a1, a2, …, an). Servo and sensor values
	2	3	(x,y) current position
	2	4	(α) current direction
3	2	3	(x,y) current position
	3	4	(D,δ) distance to the objective and the direction to follow
4	2	4	(α) current direction
	3	4	(D,δ) distance to the objective and the direction to follow
	4	1	(V1,V2) motor speeds

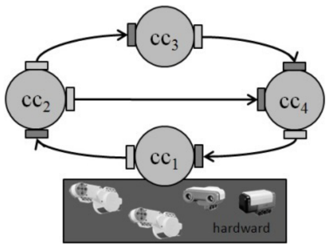

Figure 3: Logical architecture of control centres, behaviour 1

Each of the modules was implemented as an agent that performed a particular function and that transmitted the results of its operations to the next control centre or physical system. The logical architecture of the system was as follows:

4.3.2 Behaviour 2: robot that moves from A to B avoiding obstacles.

Level 1: given a specific point where the robot currently is located, initially (0,0), it must move to a destination point (A,B) avoiding possible obstacles that it might find on its route.

Level 2: (1) be capable of communicating with the hardware (to receive sensor values or to communicate values to motors), (2) know the current position as a function of the movements performed, (3) calculate the distance and the direction necessary to reach the objective, (4) perform the movement of the robot, (5) detect obstacles at the front, (6) modify the route of (4) to avoid obstacles detected in (5).

Level 3: the following table describes in each module; what communication takes place, module of origin, module of destination and signals transmitted.

Table 3: Description of the signals transmitted between modules

cc	S	T	Signal
1	4	1	(V1,V2) motor speeds
	1	2	(a1, a2, …, an). Servo and sensor values
	1	5	(a1, a2, …, an). Servo and sensor values
2	1	2	(a1, a2, …, an). Servo and sensor values
	2	3	(x,y) current position
	2	4	(α) current direction
3	2	3	(x,y) current position
	3	6	(D,δ) distance to the objective and the direction to follow
4	2	4	(α) current direction
	6	4	(D,ε) distance to the objective and the direction to follow
5	1	5	(a1, a2, …, an). Servo and sensor values
	5	6	(β,γ) angles between which there are obstacles
6	3	6	(D,δ) distance to the objective and the direction to follow
	5	6	(β,γ) angles between which there are obstacles
	6	4	(D,ε) distance to the objective and the direction to follow

With this new behaviour, the system was structured as show figure 4. As can be seen, in the new behaviour the most reactive modules are preserved such as the calculation of position and movement, and a new module appeared that was responsible for detecting obstacles and another for modifying the trajectory to follow as a function of the desired trajectory (3) and the existing obstacles (5).

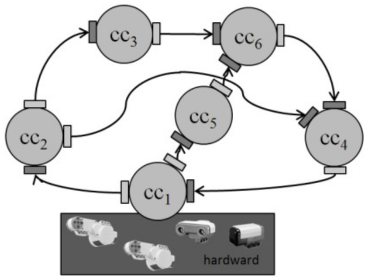

Figure 4: Logical architecture of control centres, behaviour 2

5. TESTS AND VALIDATION

We selected web services technology for the implementation of the system. This technology enabled us to maintain a high degree of decoupling between the various modules at the same time as organising the system in a distributed way. The communication between the various modules was by the passing messages using the subscription mechanism between control centres. The development platform selected was Microsoft Robotics Development Studio, a new environment specialising in the development of services orientated to robotics.

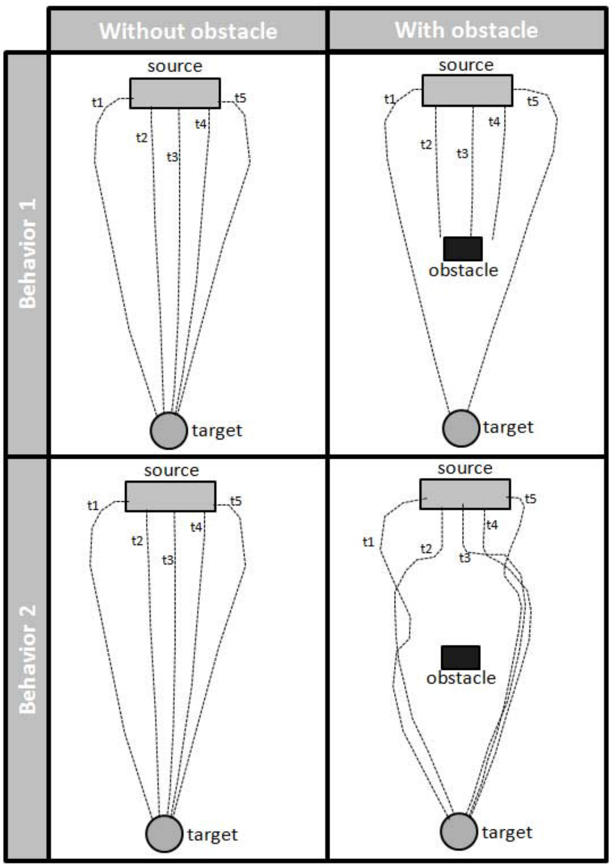

Figure 5: Test of trajectories.

The two behaviours described above were implemented. The first behaviour was that responsible for giving robot the ability to move, but it was not capable of avoiding obstacles as shown in Figure 5. The implementation of the second behaviour consisted in adding modules 5 and 6 described above with their corresponding connections. Using these modules, the control system was capable of detecting obstacles and avoiding them, preserving the global objective of the system to reach the destination. Figure 5 shows the various trajectories described by the robot both with behaviour 1 and 2. As can be observed, the robot was situated with different orientations to check that the control centres responsible for regulating the robot's direction were capable of directing the robot to its destination. As was expected, in behaviour 1, when the robot was faced with an obstacle, it collided with it, making it impossible for the robot to reach the objective.

The implementation enabled us to verity that using a system based on decentralised control centres, whose local objectives described particular functions, produced the movement of the robot as an emergent behaviour of the system. When there were centres responsible for the functionality of locating and avoiding obstacles, the robot was able to go past objects blocking its route.

6. CONCLUSIONS

This paper presented a model of a control system for robotic systems inspired by the functionality and organisation of human neuroregulatory system. Its specification was carried out using software agents in which each agent corresponds to a neuroregulatory centre and its implementation was achieved via Web Services. This system allows the implementation of the control logic of a robotic system with relative ease, in an incremental way, using the addition of new control centres to the system as its behaviour is observed or needs to be detailed with greater precision, without the need to modify existing functionality. The process is similar to the natural evolution of the nervous system.

The system preserves all the desirable features from the biological point of view (multi-layered system, independent control centres, autonomy, interconnection, division of functionalities, reactive capacities) since it is based on the functioning and organisation of the neuroregulatory system. It also has software features (modularity, decentralisation, standards, security, homogeneity) as it uses the agent paradigm and is implemented via Web Services technology.

Currently we are working on two aspects. Firstly, on the construction of control centres that implement more functionalities and so enable more complex emergent behaviours (controlling steps and limits, constructing maps and modifying trajectories in order not to repeat routes in search of the objective). Secondly on the incorporation of knowledge to the system through the use of ontologies. Ontologies enable the specification of the function to undertake (for example, autonomous mobile vehicle) and can construct the control system by the search and association of the control centres necessary to provide this functionality. This feature will also allow that, if a control centre should fail, the search and substitution of the control centre by another in a dynamic way during the execution of the system.

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